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Effect of Soil Stabilization Using Cement, Cement Kiln Dust, and L.C.S.S. on Rigid Pavement Design

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Abstract: The main objective of this research is to study the effect of stabilizing the soil, which classified as A-2-4 according to AASHTO soil classification system, with Ordinary Portland Cement (OPC), Cement Kiln Dust (CKD) and a new Liquid Chemical Soil Stabilizer (LCSS) on the rigid pavement structural design for many classes of highways in Egypt. CKD contents were 4%, 8% and 12% by soil dry weight. Whereas OPC contents were 4%, 6%, 8%, and 10%. To study the effect of the LCSS, the same contents of OPC and CKD were used with adding the LCSS, whose concentration was 1:1000 by volume of water. The values of the composite modulus of subgrade reaction in case of treated and untreated soil were determined. According to the AASHTO Guide for Design of Pavement Structures, the required pavement sections of many classes of highways were determined, for all cases of the treated and untreated soil. Finally, for each case of the treated and untreated soil, the construction cost of one square meter of pavement was estimated to study the economic feasibility of using OPC, CKD and LCSS as chemical soil stabilizers for rigid pavement construction purposes.

Keywords: Soil stabilization, Rigid pavement design, Cement kiln dust, Cement.

1. Introduction

Highways network control, to a great extent, the economic development of any country. Subgrade soil properties affect the highways' pavement structural design, construction cost, and maintenance cost. So, improving soil properties by using chemical stabilization was studied by several researchers. Soil stabilizers are developed continuously. So, the main objective of this research is to study the effect of stabilizing the soil, which classified as A-2-4 according to AASHTO soil classification system, with Ordinary Portland Cement (OPC), Cement Kiln Dust (CKD) and a new Liquid Chemical Soil Stabilizer (LCSS) on the rigid pavement structural design for many classes of highways in Egypt.

2. LITERATURE REVIEW

2.1 Rigid Pavement Structural Design

Portland cement concrete slab is the major component of the rigid pavement. Concrete slab is placed either directly on the compacted subgrade or on a subbase layer. The subbase layer may be granular or stabilized material [1]. There are several methods for rigid pavement design [2]: theoretical methods, empirical methods, and methods based on pavement performance. Throughout this research, the pavement performance method was applied. The American Association of State Highway and Transportation Officials (AASHTO) method was applied for the evaluation of the effect of soil stabilization on the rigid pavement structural design.

Rigid pavement structural design aims to obtain a pavement section capable of withstanding the wheel-imposed loads from the traffic in addition to stresses imposed by environmental effects. Pavement section should be strong enough to resist the applied stresses and transfer them safely to the subgrade [2]. Subgrade is the compacted natural earth immediately below the pavement layers [3]. There are several factors affecting the structural design of rigid pavement include [1, 4, 5, 6, and 7]:

- Traffic and loading (e.g. axle load, number of repetition, and contact area)
- Environmental factors (e.g. temperature and precipitation)
- Failure criteria (e.g. fatigue cracking, erosion, and joint deterioration)
- Concrete slab characteristics (e.g. modulus of elasticity and modulus of rupture)
- Design reliability
- Pavement management system
- Subbase characteristics (e.g. strength and quality of drainage)
- Subgrade soil properties (e.g. strength and volume stability)

2.2 Subgrade and Subbase Properties

In rigid pavement design, Subgrade and subbase materials should be characterized by their strength. There are several factors that affect subgrade and subbase strength such as [2 and 3]:

- Soil type (coarse-grained soil has generally higher strength than fine-grained soils)
- Particles size distribution and shape (Angular well-graded coarse-grained soil and aggregate have high strength)

- Dry density (As the dry density increases, strength increases)
- Moisture content (moisture content affects the dry density which achieved through compaction, and hence affects the strength and resistance to deformation under loads).

If the concrete slab is placed directly on the subgrade, subgrade strength and resistance to deformation are characterized in terms of the modulus of subgrade reaction (K), which is defined as the stress ($\mathrm{lbs/in^2}$) that will cause an inch deflection. Values of K can be obtained by conducting a plate-bearing test [3]. Estimates of K ($\mathrm{lbs/in^3}$) can also be made by correlating with other properties, as shown in equation 1 [5]. In which, $\mathrm{M_r}$ is the subgrade resilient modulus in ($\mathrm{lbs/in^2}$).

$$K = \frac{M_r}{19.4} \tag{1}$$

The subbase layer is required to (1) provide a uniform support to sustain traffic loads, (2) minimize pumping, (3) promote lateral drainage within the pavement structure, and (4) resist the adverse effects caused by pumping erosion and soil expansion [8].

If the concrete slab is placed on a subbase layer, the composite strength of the subgrade and subbase is characterized in terms of the composite modulus of subgrade reaction, which depends on [5]:

- The stiffness (stress-strain relationship under traffic loading) of the subgrade and subbase materials (expressed in terms of their resilient modulus, $\mathrm{M_r}$, values)
- The thickness of the subbase layer
- The effect of the potential loss of support arising from subbase erosion and/or differential vertical soil movements
- The presence of rigid foundation near the subgrade surface (bedrock lies within 10 feet from the subgrade surface).

  Whenever the desirable soil proprieties such as strength are improved, and the undesirable ones like high plasticity are excluded, the thickness of the required pavement – above this soil – is reduced. For instance, there would be no need for using the subbase layer. This definitely leads to the reduction of the construction cost of pavement. In brief, this is the main objective of soil stabilization.

2.3 Soil Stabilization

Soil stabilization is a process of treating a soil in such a manner as to maintain, alter or improve the performance of the soil as a construction material [2]. The changes in soil properties are brought about either by a chemical or mechanical treatment [9]. Chemical stabilization is the fundamental of this study. and, therefore, throughout the rest of this research, the term soil stabilization will mean chemical stabilization. In chemical stabilization, soil stabilization depends mainly on chemical reactions between stabilizing agents, soil, and/or groundwater [10].

Soil stabilization aims at [11 and 12]: (1) improving soil strength, stiffness, load-carrying and stress-distributing characteristics; (2) increasing soil durability; (3) bringing about economy in the cost of a highway construction by using locally available substandard materials; (4) eliminating or decreasing certain undesirable properties of soils such as excessive swelling or shrinkage and high plasticity.

Cement is the oldest stabilizing agent since the use of soil stabilization technology in 1960's [11]. It may be considered as primary stabilizing agent or hydraulic binder because it can be used alone to bring about the stabilizing action required [10]. Cement reaction is not dependent on soil minerals, and the key role is its reaction with water that may be available in any soil [10]. This can be the reason why cement is used to stabilize a wide range of soils.

[13] investigates the effects of soil stabilization using CKD, class C fly ash, and quick lime on the strength (characterized in terms of the unconfined compressive strength, UCS) and stiffness (characterized in terms of the resilient modulus, $\mathrm{M_r}$) of a variety of soil types (representing low plastic to highly plastic materials containing various amounts of clay, silt and sand). As a result of this effort, it can be concluded that:

- Soil stabilization using the previously mentioned stabilizing agents leads to increase the soil $\mathrm{M_r}$ and UCS.
- $\mathrm{M_r}$ and UCS increase with curing time, more rapidly at first.
- The following power models (equations 2, 3, and 4) provide a good mathematical description of the evolution of $\mathrm{M_r}$ and UCS with curing time. These models take into consideration the following essential characteristics of the soil, additive, and soil-additive combination:
  - The amount of fines in the untreated soil (percent passing sieve # 200, F)
  - The fines nature in the untreated soil (plasticity index, PI)
  - The amount of additive used (as a percent of soil dry weight, AC)
  - the relative effectiveness of the additive mixed with the soil ($\mathrm{M_r}$ and UCS after one-day curing period, $\mathrm{M_{r\,1}}$ and $\mathrm{UCS_1}$ respectively)

$$\mathrm{UCS_t = UCS_1 * t^{Rtu}} \tag{2}$$

$$\mathrm{M_{r\,t} = M_{r\,1} * t^{Rt}} \tag{3}$$

$$\mathrm{Rtu\ or\ Rt} = \mathrm{m_1} * \left(\frac{1}{\mathrm{F}}\right) + \mathrm{m_2} * \mathrm{PI} + \mathrm{m_3} * \mathrm{AC} + \mathrm{m_4} * \left(\frac{\mathrm{UCS_1}}{\mathrm{P_a}}\right) - \mathrm{b} \tag{4}$$

Where:

- $\mathrm{UCS_t}$ and $\mathrm{M_{r\,t}}$ are the $\mathrm{M_r}$ and UCS after (t) days curing period.
- Rtu and Rt are the rate exponents of the UCS and $\mathrm{M_r}$ models respectively.
- $\mathrm{m_1}$, $\mathrm{m_2}$, $\mathrm{m_3}$, $\mathrm{m_4}$, and b are coefficients developed from a multivariable linear regression analysis.

[14] investigates the effects of soil stabilization using CKD on soil plasticity (Atterberg limits), swell potential (free swell testing), strength (UCS), and durability (leaching and wet-dry tests) of a variety of soil types. [14] obtain that: (1) soil plasticity and swell potential were reduced; (2) soil strength was increased; (3) substantial strength was retained after leaching; and (4) CKD stabilized soil performance in wet-dry testing was similar to that for cement, lime, and fly ash stabilized soil.

Other researchers investigated the effects of other stabilizing agents such as granulated blast furnace slag [15 and 16], sewage sludge ash [17], and rice husk ash [18]. All of these researches proved the improvement of the engineering properties of the stabilized soil. The development is still going on; as new materials are always being examined as soil stabilizers. This is what was done in this research by examining the new material, LCSS, as a soil stabilizer when added beside OPC and CKD.

3. MATERIALS PROPERTIES

The properties of both the used stabilizing agents, the untreated soil, and the stabilized soil with OPC and CKD (whether the LCSS is added or not) are presented in [19]. Table 1 displays the M_r values of the treated and untreated soil, as shown in [19].

TABLE 1. Resilient Modulus of the Treated and Untreated Soil

OPC Content (%)	Without Adding LCSS	With Adding LCSS	CKD Content (%)	Without Adding LCSS	With Adding LCSS
0%	24,313.93	25,095.10	0%	24,313.93	25,095.10
4%	47,428.49	60,942.82	4%	26,419.24	33,546.57
6%	128,668.65	209,757.18	8%	66,796.03	76,710.35
8%	250,731.41	273,048.19	12%	56,152.07	64,953.27
10%	437,266.42	323,986.76			

4. RIGID PAVEMENT DESIGN IN CASE OF USING THE GRANULAR SUBBASE LAYER

4.1 Determination of the Composite Modulus of Subgrade Reaction

For untreated soil, the concrete slab is assumed to be placed on a granular subbase layer, whose CBR is 80%. The first step in rigid pavement design is the estimation of the composite modulus of subgrade reaction by assuming different thicknesses for the granular subbase layer ($\mathrm{t_{GSB}} = 15$ to 45 cm).

The granular subbase resilient modulus ($\mathrm{M_{r\,GSB}} = 40{,}313.29\ \mathrm{lbs/in^2}$) was calculated using equation 5 [4]. The untreated subgrade resilient modulus ($\mathrm{M_{r\,Soil}}$) is $24{,}313.928\ \mathrm{lbs/in^2}$. By using $\mathrm{M_{r\,GSB}}$ and $\mathrm{M_{r\,Soil}}$, the composite modulus of subgrade reaction ($\mathrm{K_\infty}$) values were determined, as shown in Fig. 1, at the different values of $\mathrm{t_{GSB}}$.

M_r=4920*(CBR)^0.48 (5)

By assuming that the depth from the subgrade surface to the bed rock is greater than 10 ft., K_∞ values were not corrected for the presence of rigid foundation near the subgrade surface. Figure 2 shows the determination of the corrected composite modulus of subgrade reaction (K) taking into consideration the effect of potential erosion of the subbase, by assuming that the loss of support factor is 1.

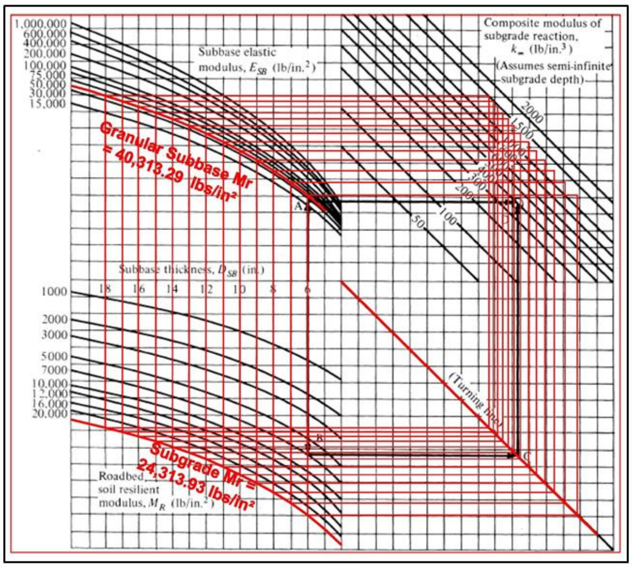

Fig 1. Determination of K_∞ of Untreated Soil and Granular Subbase Layer

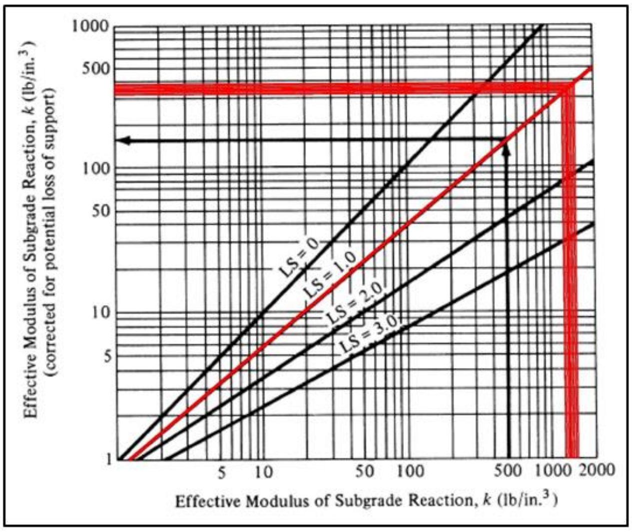

Fig 2. Correction of $\mathrm{K_\infty}$ Taking into Consideration the Potential Loss of Support

In case of the stabilized soil with the LCSS only or with 4% CKD (whether the LCSS was added or not), the stabilized soil resilient modulus (M_(r S.S.)) values are less than the granular subbase resilient modulus (M_(r GSB)). Therefore, in these cases, the concrete slab is assumed to be placed on the granular subbase layer.

By using the values of M_(r S.S.) and M_(r GSB), and by following the same procedure, the values of the corrected composite modulus of subgrade reaction (K) were determined. Table 2 displays the K values in case of using the granular subbase layer.

4.2 Design Inputs and General Calculations

Tables 3 and 4 show the design inputs and general calculations, which were used to design the required rigid pavement for many classes of highways in Egypt, according to [4 and 5].

4.3 Pavement Design of Arterial (Heavy Traffic) Highways

4.3.1 Case of the Untreated Soil

Table 5 shows the design inputs for designing the required rigid pavement of an arterial (heavy traffic) highway which will be constructed above the untreated soil in case of using 15cm granular subbase layer (t_GSB=15cm). By using these design inputs and the AASHTO equation for rigid pavement design, the required minimum concrete slab thickness (D=14.19 inch=36.05 cm≅36.5 cm) was calculated. By using the same design inputs (except using the appropriate K values from table 2), D values were calculated for the other values of the granular subbase layer thickness.

Table 6 displays the costing items [20 and 21], which were used to calculate the construction cost of one square meter of pavement (OSMPC). Equations 6, 7, 8, and 9 were used to calculate OSMPC at each granular subbase thickness. The rigid pavement section corresponds the minimum OSMPC was selected as a design section, as shown in Table 7.

TABLE 2. Corrected Composite Modulus of Subgrade Reaction in Case of Using the Granular Subbase Layer

CKD Content (%)		K (lbs/in^3) at Subbase Thickness (cm)												
		15	17.5	20	22.5	25	27.5	30	32.5	35	37.5	40	42.5	45
Without Adding LCSS	0%	332.7	334.3	338.8	347.2	352.2	357.4	359.2	365.5	370.7	372.9	379.8	382.7	388.1
	4%	353.5	354.9	359.0	368.6	373.8	379.8	380.9	387.4	392.5	394.3	401.4	403.4	408.7
With Adding LCSS	0%	337.7	339.3	343.8	352.4	357.4	362.8	364.6	370.9	376.0	378.0	385.2	387.9	393.2
	4%	417.3	417.7	420.6	432.0	437.7	444.3	444.7	451.7	456.0	456.9	464.0	464.5	469.9

TABLE 3. Pavement Design Inputs

Design Inputs	Arterial Highway	Collector Highway	Local Highway
Annual average daily traffic, AADT, (veh/day)	15,000	6,000	4,500
Percent of trucks, %T, (%)	32.5%	35%	20%
Truck factor, TF, (standard axle/truck)	6.54	6.54	6.54
Directional distribution factor, D. D.	0.5	0.5	0.5
Lane distribution factor, L. D.	0.8	0.8	0.9
Analysis period, n, (years)	25	25	25
Traffic annual growth rate, r, (%)	2%	2%	2%
Design reliability, R, (%)	90%	90%	80%
Overall standard deviation, S_0.	0.35	0.35	0.35
Initial present serviceability index, P_i.	4.5	4.5	4.5
Terminal present serviceability index, P_t,	2.5	2	1.5
Granular subbase M_r, $M_{r\,GSB}$, (lb/in^2)	40,313.29		
Concrete modulus of rupture, (S'_C), (lb/in^2)	620		
Concrete modulus of elasticity, E_C, (lb/in^2)	$5 * 10^6$		
Load transfer coefficient, J	2.8		
Subbase drainage coefficient, C_d,	1		

TABLE 4. General Calculations of Pavement Design

General Calculations	Arterial Highway	Collector Highway	Local Highway
Traffic annual growth factor, G. F.	32.03		
Cumulative equivalent single axle load application, W_{18}, (Standard axle)	149,096,081	64,226,004	30,966,110
The standard normal deviate, Z_R	-1.282	-1.282	-0.841
Present serviceability loss, Δpsi.	2.0	2.5	3.0

TABLE 5. Design Inputs for Pavement Design of an Arterial Highway in Case of Untreated Soil and 15cm Granular Subbase

Input Parameter	Z_R	S_0	W_{18}	Δpsi	P_t	S'_C	C_d	J	E_C	K
Value	-1.282	0.35	149,096,081	2.0	2.5	620	1	2.8	$5 * 10^6$	332.7

TABLE 6. Costing Items for the Calculation of OSMPC

Costing Item	Unit	Unit Cost (EGP)
Concrete Slab	m3	2,500
Granular Subbase *	m3	200*
Earth works (Mixing, Compaction, etc.) for Treated Soil Layer	m3	40
OPC	ton	1,250
CKD	ton	150
LCSS	m3	100,000

* This unit cost is estimated provided the granular subbase transportation distance ($GSBTD$) equals 20 km. However, every extra kilometer in the $GSBTD$ increases the unit cost by one EGP.

$$\mathrm{CSC} = (\mathrm{D} * 1 * 1) * \mathrm{CSUC} \tag{6}$$

$$\mathrm{GSBLUC} = \mathrm{GSBLUC}_{\mathrm{Initial}} + (1 * [\mathrm{GSBTD} - 20]) \tag{7}$$

$$\mathrm{GSBLC} = (\mathrm{t}_{\mathrm{GSB}} * 1 * 1) * \mathrm{GSBLUC} \tag{8}$$

$$\mathrm{OSMPC} = \mathrm{CSC} + \mathrm{GSBLC} \tag{9}$$

Where:

- D and $\mathrm{t}_{\mathrm{GSB}}$ are the thicknesses (m) of the concrete slab and the granular subbase layer respectively.
- CSC and GSBLC are the construction costs (EGP) of one square meter of the concrete slab and the granular subbase layer respectively. Whereas CSUC and GSBLUC are the units' costs of both.
- $\mathrm{GSBLUC}_{\mathrm{Initial}}$ is the construction cost (EGP) of one cubic meter of the granular subbase layer, at granular subbase transportation distance (GSBTD) equals 20km.

4.3.2 Case of the Stabilized Soil

M_r values of the stabilized soil are lower than the granular subbase M_r, in case of the stabilized soil with only LCSS or with 4% CKD (with or without adding the LCSS). Therefore, in these cases, the granular subbase layer was used above the treated soil layer. The shown design inputs in table 5 (except using the appropriate K values from table 2) were used to calculate the concrete slab thicknesses at the different granular subbase thicknesses.

Equations 10, 11, 12, 13, 14, and 15 were used to calculate the construction cost of one square meter of the treated soil layer (TSLC). Consequently, the OSMPC values were calculated by using equation 16. Rigid pavement sections which correspond the minimum OSMPC were selected as a design sections. Table 7 displays the selected pavement sections for the arterial (heavy traffic) highways when using the granular subbase layer.

$$W_s = (0.95 * \gamma_{d\,max}) * (t_{TSL} * 1 * 1) \tag{10}$$

$$AC = AP * W_s * AUC \tag{11}$$

$$LCSSV = LCSSP * (W_s * O.M.C.) \tag{12}$$

$$LCSSC = LCSSV * LCSSUC \tag{13}$$

$$EWC = EWUC * (t_{TSL} * 1 * 1) \tag{14}$$

$$TSLC = AC + LCSSC + EWC \tag{15}$$

$$OSMPC = CSC + GSBLC + TSLC \tag{16}$$

Where:

- $\mathrm{W_s}$ is the dry weight (ton) of one square meter of the treated soil layer before adding the traditional additive (OPC or CKD).
- $(0.95 * \gamma_{d\,max})$ is the field dry weight (ton) of one cubic meter of soil that is compacted to a dry density equals 95% of the maximum dry density ($\gamma_{d\,max} = 1.972\ ton/m^3$).
- t_{TSL} is the thickness of the treated soil layer ($t_{TSL} = 0.3m$).
- AC is the cost (EGP) of the required weight of the additive (OPC or CKD) for stabilizing one square meter of the treated soil layer. Whereas AUC is the additive (OPC or CKD) unit cost (EGP).
- AP is the additive (OPC or CKD) percent by soil dry weight.
- $LCSSV$ is the required volume of the $LCSS$ (m^3) for stabilizing one square meter of the treated soil layer.
- $LCSSP$ is the $LCSS$ concentration with respect to water volume (0.001 m^3 of $LCSS$ for 1 m^3 of water).
- $O.M.C.$ is the optimum moisture content of the treated soil layer (12.38%).
- $LCSSC$ is the cost (EGP) of the required volume of the $LCSS$ for constructing one square meter of the treated soil layer. Whereas $LCSSUC$ is the unit cost (EGP) of the $LCSS$.
- EWC is the cost (EGP) of mixing, compacting, etc. of one square meter of the treated soil layer. While $EWUC$ is the unit cost (EGP) of earth works.
- $TSLC$ is the construction cost (EGP) of one square meter of the treated soil layer.

4.4 Pavement Design of Collector and Local Highways

By following the same procedure of designing the pavement of arterial (heavy traffic) highways, the required pavements of collector and local highways were designed. Tables 8 and 9 display the selected rigid pavement sections which correspond the minimum OSMPC in cases of the collector and local highways respectively.

5. RIGID PAVEMENT DESIGN IN CASE OF USING THE TREATED SOIL AS A SUBBASE LAYER

$\mathrm{M_r}$ values of the stabilized soil ($\mathrm{M_{r\,S.S.}}$) are greater than the granular subbase $\mathrm{M_r}$, in case of the stabilized soil with OPC or with 8% and 12% CKD (with or without adding the LCSS). Therefore, in these cases, the pavement section was designed considering utilizing the stabilized soil as a subbase layer.

Table 1 displays the $\mathrm{M_{r\,S.S.}}$ values. the untreated soil resilient modulus ($\mathrm{M_{r\,Soil}}$) is 24,313.93 $\mathrm{lbs/in^2}$. As in case of using the granular subbase layer, the values of the corrected composite modulus of subgrade reaction (K) were determined at the different thicknesses of the treated soil layer ($\mathrm{t_{TSL}} = 15$ to 45 cm), by using $\mathrm{M_{r\,S.S.}}$ and $\mathrm{M_{r\,Soil}}$ values. Table 10 displays these K values.

As in case of using the granular subbase layer, concrete slab thicknesses at the different subbase thicknesses were determined, for each OPC or CKD content. By using equation 17, OSMPC was calculated in each case. Tables 11 and 12 display the selected rigid pavement sections which correspond the minimum

OSMPC in case of using the stabilized soil with OPC and CKD respectively as a subbase layer.

Figure 3 displays the savings in OSMPC, which result from using the stabilized soil with OPC and CKD as a subbase layer instead of the traditional granular subbase layer.

$$OSMPC = CSC + TSLC \qquad (17)$$

TABLE 7. Selected Pavement Sections in Case of Arterial (Heavy Traffic) Highways When Using the Granular Subbase Layer

CKD Content (%)		Thickness (cm)			OSMPC (EGP) in case of GSBTD (km)				
		D	t_{GSB}	t_{TSL}	20	40	60	80	100
Without LCSS	0%	36.5	15	0	942.5	945.5	948.5	951.5	954.5
	4%	36	15	30	945.4	948.4	951.4	954.4	957.4
With LCSS	0%	36.5	15	30	961.5	964.5	967.5	970.5	973.5
	4%	36	15	30	952.3	955.3	958.3	961.3	964.3

TABLE 8. Selected Pavement Sections in Case of Collector Highways When Using the Granular Subbase Layer

CKD Content (%)		Thickness (cm)			OSMPC (EGP) in case of GSBTD (km)				
		D	t_{GSB}	t_{TSL}	20	40	60	80	100
Without LCSS	0%	30.5	20	0	802.5	806.5	810.5	814.5	818.5
	4%	30.5	15	30	807.9	810.9	813.9	816.9	819.9
With LCSS	0%	30.5	15	30	811.5	814.5	817.5	820.5	823.5
	4%	30.5	15	30	814.8	817.8	820.8	823.8	826.8

TABLE 9. Selected Pavement Sections in Case of Local Highways When Using the Granular Subbase Layer

CKD Content (%)		Thickness (cm)			OSMPC (EGP) in case of GSBTD (km)				
		D	t_{GSB}	t_{TSL}	20	40	60	80	100
Without LCSS	0%	25	15	0	655.0	658.0	661.0	664.0	667.0
	4%	25	15	30	670.4	673.4	676.4	679.4	682.4
With LCSS	0%	25	15	30	674.0	677.0	680.0	683.0	686.0
	4%	24.5	15	30	664.8	667.8	670.8	673.8	676.8

TABLE 10. Corrected Composite Modulus of Subgrade Reaction in Case of Using the Stabilized Soil as a Subbase Layer

t_{TSL} (cm)	Corrected Composite Modulus of Subgrade Reaction, K, (lbs/in^3)											
	CKD Content (%)				OPC Content (%)							
	Without $LCSS$		With $LCSS$		Without $LCSS$				With $LCSS$			
	8%	12%	8%	12%	4%	6%	8%	10%	4%	6%	8%	10%
15	352.9	345.2	360.5	352.0	337.2	391.5	434.8	469.4	349.0	426.0	439.3	450.5
17.5	359.4	352.2	367.1	358.5	343.1	406.0	451.8	493.2	355.8	442.1	456.6	469.1
20	369.8	360.8	379.1	368.6	350.6	420.0	474.5	519.3	365.3	464.7	479.3	491.9
22.5	376.7	366.8	387.0	375.6	359.2	433.5	494.1	542.7	371.8	482.4	500.2	516.3
25	385.4	374.9	396.3	384.1	364.4	445.4	509.8	566.6	380.0	496.9	516.5	533.4
27.5	393.4	382.3	404.7	392.1	369.8	456.4	528.7	590.4	387.9	514.3	536.1	555.1
30	400.3	388.5	412.4	398.7	373.8	465.6	543.8	612.3	394.3	528.3	551.8	571.8
32.5	406.3	393.4	419.1	404.5	381.6	474.5	563.0	636.8	399.9	546.5	571.4	592.9
35	414.9	401.2	428.9	413.1	388.1	486.7	580.0	662.6	408.0	561.9	589.0	612.6
37.5	420.6	405.4	436.0	418.6	391.0	499.4	596.2	683.2	412.9	577.6	605.8	630.5
40	430.9	415.3	446.7	429.0	400.7	509.8	617.0	710.2	423.0	595.8	627.7	655.7
42.5	439.0	422.6	456.0	437.1	407.8	525.0	632.7	742.2	430.7	610.2	644.0	673.7
45	448.0	429.8	466.4	445.8	413.8	540.3	653.7	773.8	438.8	629.2	666.5	699.3

TABLE 11. Selected Rigid Pavement Sections in Case of Using the Stabilized Soil with OPC as a Subbase Layer

Highway Classification	OPC Content (%)	Without $LCSS$			With $LCSS$		
		Thickness (cm)		$OSMPC$ (EGP)	Thickness (cm)		$OSMPC$ (EGP)
		D	t_{TSL}		D	t_{TSL}	
Arterial	4%	36	20	926.4	36	15	923.2
	6%	36	15	926.7	36	15	930.1
	8%	36	15	933.5	36	15	937.0
	10%	35.5	17.5	934.7	36	15	943.9
Collector	4%	30.5	15	782.3	30.5	15	785.7
	6%	30.5	15	789.2	30	20	790.2
	8%	30	20	794.7	30	20	799.4
	10%	30	15	790.4	30	17.5	801.2
Local	4%	25	15	644.8	25	15	648.2
	6%	24.5	20	648.0	24.5	15	642.6
	8%	24.5	15	646.0	24.5	15	649.5
	10%	24.5	15	652.9	24.5	15	656.4

TABLE 12. Selected Rigid Pavement Sections in Case of Using the Stabilized Soil with CKD as a Subbase Layer

Highway Classification	CKD Content (%)	Without $LCSS$			With $LCSS$		
		Thickness (cm)		$OSMPC$ (EGP)	Thickness (cm)		$OSMPC$ (EGP)
		D	t_{TSL}		D	t_{TSL}	
Arterial	8%	36	15	909.4	36	15	912.9
	12%	36	15	911.1	36	15	914.5
Collector	8%	30.5	15	771.9	30.5	15	775.4
	12%	30.5	15	773.6	30.5	15	777.0
Local	8%	24.5	35	634.4	25	15	637.9
	12%	25	15	636.1	25	15	639.5

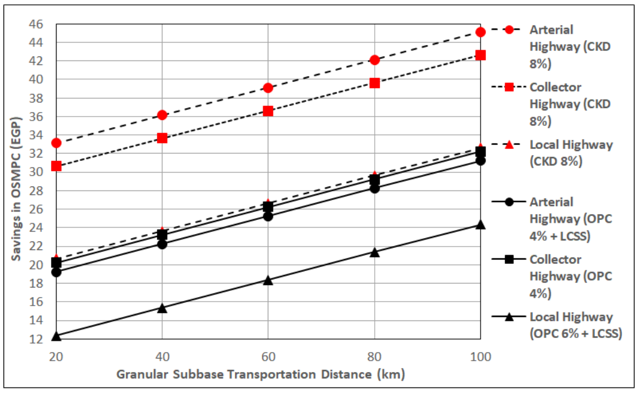

FIGURE 3. Savings in OSMPC When Using the Stabilized Soil as a Subbase Layer

6. CONCLUSIONS

- In regard to the composite modulus of subgrade reaction (K):
  - Subgrade stabilization leads to increase its stiffness, which is characterized in terms of its resilient modulus. As the subgrade stiffness increases, the required subbase thickness decreases, to achieve a particular K value.
  - At a particular subgrade stiffness, the greater the subbase thickness is, the higher the K value is.
  - Addition of the LCSS leads to improving K except for 10% OPC content.
  - The optimum CKD content is 8% (whether the LCSS is added or not).
  - The greater the OPC content is, the higher the K value is (whether the LCSS is added or not).
  - The best effect for adding the LCSS was at 6% OPC content.
- In Regard to the economic feasibility of soil stabilization:
  - Soil stabilization using CKD is more economical than using OPC.
  - Addition of the $LCSS$ leads to increase the $OSMPC$, except at:
    - 4% OPC content, for arterial highways.
    - 6% OPC content, for local highways.
    - 4% CKD content, for local highways.

- For all highway classes, using the stabilized soil layer with 8% CKD as a subbase layer is the most economical solution.
- The further away the granular subbase quarries are, the more economically feasible is the use of the stabilized soil as a subbase layer than the use of the granular subbase layer.

7. RECOMMENDATIONS

Based on the discussion presented in this research, the following suggestions for further research may be stated:

1- Investigating the effects of using the $LCSS$, beside the selected traditional stabilizers, for stabilizing the subbase materials on the concrete slab thickness.

2- Construction of test sections to measure the long-term performance of the pavement in case of the stabilized soil.

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